Ultra-high energy cosmic rays detected with experimental array of Pierre Auger Observatory

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Abstract. A contemporary status of the field of cosmic rays with extremely high energies is reviewed, mainly from the experimental point of view. In our focus is the largest detector – Pierre Auger Project, which is in these years being built in Argentina. The contribution of Czech group within this international project is described in detail.

Introduction – Problem of cosmic rays with extremely high energies

Cosmic rays as the observable physical phenomenon are among the most puzzling problems of astrophysics and physics almost for the whole century. Discovered by Victor Hess in 1912, cosmic rays are known as the stream of high-energy particles, incoming from space and continually hitting the Earth's atmosphere from all directions. The majority of cosmic rays are composed of protons, other components are heavier nuclei and electrons.

The singularity of some cosmic rays is stressed by the fact that their energies are higher than any other observed elsewhere in nature. In recent years, research of so called EHECRs or UHECRs (that means cosmic ray particles with extremely high energies) is the most intensive one *[e.g. Nagano, M. & Watson A.A., 2000]*. These particles are moving with speed almost equal to speed of light (gamma factors up to 10^{12}); energies of such particles are hundred million times higher than those of particles from largest man-made accelerators. Actually, on October 15th 1991 the Fly's Eye Detector located in Utah, USA trapped the most energetic particle ever detected. It was probably a proton, with energy 3×10^{20} eV or 50 J, which is comparable to the energy of a tennis ball moving with speed about 80 kilometres per hour.

The most energetic cosmic rays attract the greatest part of attention, because while cosmic rays with lower energies (10^{11} up to 10^{18} eV) are accelerated mainly in supernovae, sites of origin of cosmic rays with highest energies (10^{18} to 10^{20} eV) are up to now completely unknown and probably extragalactic. Problem with search of possible sites of origin of UHECRs is widely enhanced by the existence of the so-called Greisen-Zatsepin-Kuzmin cutoff *[Greisen, K., 1966; Zatsepin, G.T. & Kuzmin, V.A., 1966]*. Particles are losing their energy in collisions with microwave background photons, so we have to look for suitable sites of origin of ordinary particles within the so-called GZK sphere, with the radius 50 Mpc centred in the Earth. However, in such sphere, there are no suitable objects allowing accelerating protons or nuclei to energies up to 10^{21} eV employing the classical mechanism of acceleration – Fermi acceleration in variable magnetic fields.

Solution of this problem is very tempting and will be strongly fundamental – we are very probably going to discover some new physics or some new objects. However, the most important step forward is now on the experimental field – the datasets of UHECRs are critically small and we have to enlarge them at least by an order of magnitude.

Detectors of cosmic rays with extremely high energies

Pierre Auger made the second important step after Victor Hess in research of cosmic rays in the thirties. He discovered (by the use of coincidence measurements) that a primary particle of high-energy cosmic ray is creating the atmospheric shower of millions of secondary particles due to collisions with atomic nuclei in the atmosphere. Generally, the number of secondary particles is proportional to the energy of primary particle. E.g. for particle with energy about 10^{20} eV the first interaction is situated about 50 km above the sea level, then the cascade of further interactions follows, and the resulting number of secondaries on the ground is around 10^{10}. Furthermore, relative time of detection of individual secondary particles carries information about incident direction of primary particle.

Based on these facts, two types of detectors of extremely energetic cosmic rays were developed up to now: ground arrays and fluorescence telescopes. The array of ground detectors is recording and sampling fraction of secondary particles. Scintillators or water Cherenkov detectors are used as the individual stations in array. The alternative method of detection employs emission of UV and visible photons during recombination of nitrogen molecules, which were excited during collisions during the development of a shower of secondaries. The total intensity of emitted light is directly proportional to the energy of primary particle. The incident direction of primary particle could be evaluated using timing information from individual phototubes and using the reconstructed position of the projected shower plane.

Seven different detectors were in operation during last 40 years of measurements and achieved detection of approximately 200 particles with energies over 4×10^{19} eV and only about 20 particles with energies over 10^{20} eV *[Yoshida, S. & Dai, H., 1998]*. The list begins with scintillator-array detector located in Volcano Ranch, USA, in operation 1959–1963, then follows SUGAR, scintillator-array located in desert in Australia, in operation 1968 - 1979. Important place on the list has the first water Cherenkov array of detectors located in Haverah Park, UK, in operation 1968–1987. Since 1970 up to now is working scintillator array in Yakutsk, Russia. Since 1990 up to now is also working last scintillator array detector called AGASA, located in Akeno Japan. AGASA is currently the largest working detector in the world with 100 km^2 of effective area and also has largest number of detections of particles with energies above $4\text{x}10^{19}$ eV and also above 10^{20} eV. There are only two members in the group of fluorescence detectors – temporarily closed HiRes in Utah, USA, working since 1998, and its predecessor Fly's Eye, which worked from 1981–1992 and is still famous for the detection of the most energetic particle.

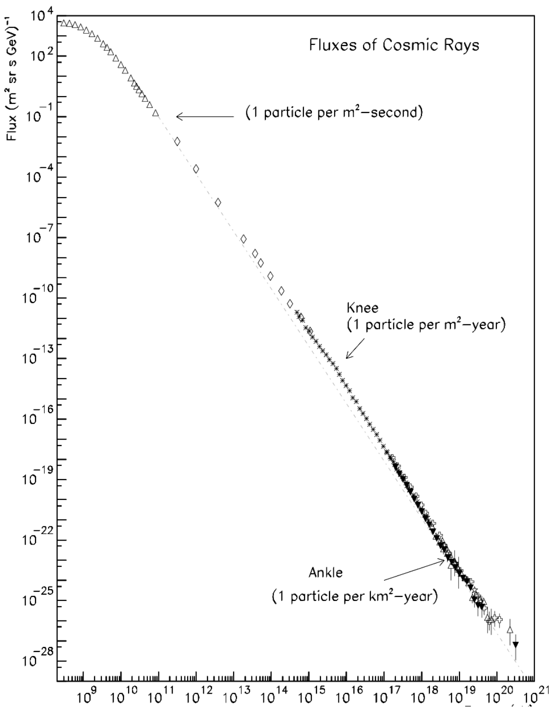

Figure 1. Observed energy spectrum of cosmic rays with energies greater than 100 MeV. The spectrum should be expressed in the form of E^{-3} power law from 10^{11} eV to 10^{20} eV. There are slight changes of slope about $10^{15.5}$ (called knee) and about $10^{18.8}$ eV (called ankle).

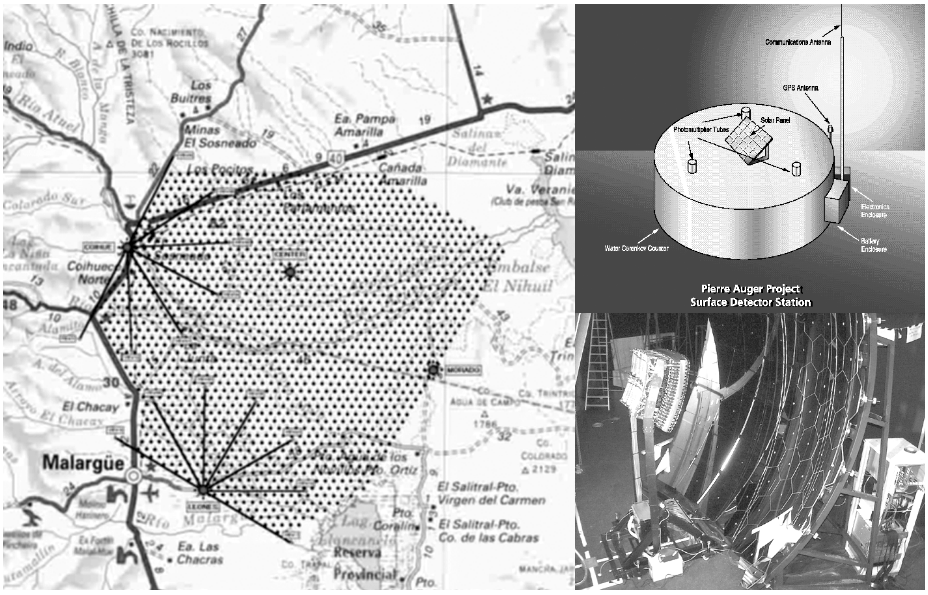

Figure 2. *(Left)* Map of the proposed array of the southern site of Pierre Auger Observatory. *(Upper right)* Scheme of Cherenkov detector station. *(Lower right)* Photograph of prototype of fluorescence telescope. Segmented mirror is composed of two mirror types – left half consists of aluminium rectangular segments, produced in Germany, and right half consists of glass hexagonal segments, produced in the Czech Republic.

Pierre Auger Project

The strong need for new data and enlarged statistics of events with extreme energies led to creation of several proposals of "new generation" detectors. For the next decade we shall have at least one space-borne fluorescence detector (EUSO) with aperture thousand times larger than the aperture of AGASA, in fifteen years the start of OWL is planned, which should be stereo fluorescence detector on orbit with even greater aperture than EUSO. On Earth's surface two main projects are planned – fluorescence Telescope Array in Utah (have to be financed mostly by Japanese groups, preparation works are now slowed down due to organizational and financial problems) and Pierre Auger Project. In these days and also within the nearest years the most important project surely is the Pierre Auger Project *[Auger Collaboration, 1997]*, because this is the only detector, which is already being built and furthermore, whose experimental array was already taking data successfully (details will follow below).

Project of the Pierre Auger Observatory is an international collaboration of 19 countries (Argentina, Armenia, Australia, Bolivia, Brazil, China, Czech Republic, France, Germany, Greece, Italy, Mexico, Poland, Russia, Slovenia, Spain, United Kingdom, USA and Vietnam) grouping together more than 300 scientists from approximately 50 institutions.

Pierre Auger Observatory (PAO) will consist of two sites – southern site is already being build in Malargüe, Mendoza province, Argentina and have to be finished in 2005; northern site should be situated in Millard County, Utah, USA and construction will have to start after the southern site will be finished. Due to this configuration, PAO will be the first detector, which will cover the whole sky and so it will be a unique tool for studies of isotropy of spatial distribution of cosmic ray events. Further uniqueness is given by fact, that PAO is so-called hybrid detector of cosmic rays. There will be ground array of water Cherenkov detectors co-operating with system of very sensitive fluorescence telescopes, the latter is dedicated to observation of very faint violet (or ultraviolet) radiation during clear moonless nights. The radiation originates as a by-product during development of cosmic-ray shower. Hybrid detector allows us to significantly increase the precision of reconstruction of shower parameters (energy and orientation of shower axis) and to reduce systematic errors of each type of measurement.

Ground detectors have to cover 3000 km^2 on each hemisphere. In fact, 1600 such detectors on each hemisphere will be distributed regularly in hexagonal grid with spacing about 1.5 km. Individual Cherenkov detectors in array will contain 12 000 litres of ultrapure water monitored by three photomultipliers.

Fluorescence telescopes will be distributed on the edges of area covered by surface detectors. There have to be constructed four "eyes" on each hemisphere, each eye consisting of six fluorescence telescopes. Detection range of these telescopes is 20 km for showers with energies about 10^{20} eV. Main optical element of each telescope is a segmented mirror with size 3.6 m×3.6 m and with a field of view 30°×30°, each telescope is equipped with 440 fast photomultipliers situated in its focus plane.

Current status of southern site of Pierre Auger Observatory

It was agreed, that in the first phase – for the test of functionality and of effectiveness of whole system – on the southern site in Argentina will be built testing and experimental array, composed of 40 surface detectors and 2 fluorescence telescopes. This phase was successfully finished in April 2002, when also the operation of prototype fluorescence detector was terminated, but the surface network is still taking interesting data.

Prototype of fluorescence detector was in operation since May 2001. Already on May 23th 2001 first showers were detected with fluorescence telescope. Ground array composed of 40 prototypes of water Cherenkov detectors started its operation shortly after – in August 2001. Hybrid events (that means showers detected together with surface array of Cherenkov tanks and with fluorescence telescope) were first detected in December 2001.

Together 78 hybrid events were detected during the whole operation of prototype array (December 2001 - April 2002). Three hybrid events with energies significantly higher than 10^{19} eV were detected, estimated energies were 2.9, 3.3 and 4.0 $\times 10^{19}$ eV. The most energetic event detected up to now with prototype of Pierre Auger southern observatory is from May 23rd 2002, its estimated energy is 6.3×10^{19} eV, the event was detected after the end of operation of fluorescence telescopes – 20 of 40 tanks in surface array were hit.

Contribution of Czech collaboration members to Project Auger

Czech Republic is represented by tightly co-operating groups of scientists from the Centre for Particle Physics, Institute of Physics, Czech Academy of Sciences and from the Joint Laboratory of Optics in Olomouc. Some participating scientists are also from Charles University in Prague, Faculty of Mathematics and Physics and from the Astronomical Institute, Czech Academy of Sciences, Ondřejov.

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The main contribution of Czech group to the project consists of the production of mirrors for fluorescence detector. In Particular, Czech group of Auger project is responsible for production of mirrors for 12 telescopes for southern site of PAO.

First base (first eye) fully equipped with fluorescence telescopes with the Czech mirrors will be situated on Coihueco hill. The building of second "eye" is intensively progressing in recent months and six fluorescence telescopes, completely equipped with Czech optics, have to be situated there up to the end of 2002.

Up to now, Joint Laboratory of Optics produced one half of mirrors for one of the prototype detectors. In comparison with these prototype segments and in order to decrease the number off necessary mirrors the final mirror segment has radius of circumscribed circle 625 mm, about 25% more than radius of prototype. As a consequence, the number of mirror segments per one telescope decreased from 85 to 60 pieces and the surface of new segments is 56% larger than it was in the prototype. With these new modifications the quality of mirrors was kept or even improved. The production of mirrors for two first telescopes on Coihueco was already finished and mirrors were shipped to Argentina in June 2002.

Aside from this main task, Czech group was responsible also for the design of corrector ring and Czech group is also participating on the development of analytical and reconstruction software (M. Boháčová). Furthermore, in the frame of diploma thesis (M. Prouza), theoretical analysis of propagation of cosmic rays with extremely high energies within magnetic field of our Galaxy was performed. In present days is being developed the model of propagation of cosmic ray particles in GRB environments based on the same engine, as was the model of GMF. In another diploma thesis (R. Šmída) the influence of Galactic magnetic field on the chemical composition of cosmic rays was studied and an improved model of regular magnetic field in Galaxy perturbed by random areas with irregular fields (eg. supernova remnants, pulsars, star formation regions) was created. This model was applied for an analysis of problem of knee and for an analysis of movement of particles with high energies from sources within our Galaxy. Special attention was given to monitoring of changes in isotropy and in chemical composition.

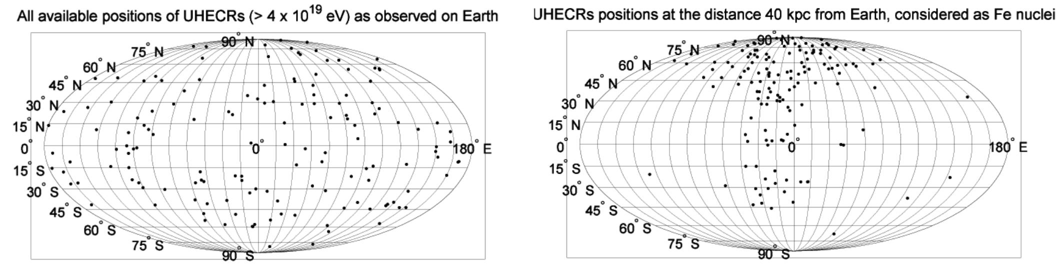

Figure 3. Initial *(left)* and final *(right)* positions of iron nuclei in the computer model of propagation of UHECRs in Galactic magnetic field. On the left panel original arrival directions of 145 UHECRs are shown. Particles were then propagated to the distance 8.5 kpc from the Earth *(right)*.

My personal research themes

Directly within Project Auger (not taking into account my theoretical work about propagation of UHECRs) I'm working on two themes. The first one is very actual and results will be used in construction of final fluorescence telescopes, the second theme is long-term, but with greater theoretical impact and will probably be one main points in my prepared PhD thesis.

A) Analysis of star images in background data of experimental array of the PAO

The values of background intensity flux are automatically saved during operation of fluorescence telescope. Star images up to fourth magnitude could be safely identified within these datasets by comparison of computed position of star from catalogue in given time (in my analysis Bright Star Catalogue was used). Results of such analysis could be used for correction of spatial orientation of individual photomultipliers and of whole telescope and for independent estimate of absolute gain and linearity of individual phototubes.

I made such analysis and found quite large (up to factor of 2) differences in sensitivities of individual phototubes and that the alignment of whole camera and even of individual photubes is very precise. In these days I'm enlarging the volume of data processed in analysis and trying to make program for automation of such analysis and finally I'm preparing the analysis of absolute gain.

B) Analysis of horizontal showers in fluorescence telescope

In previous experiments the apertures of detectors were heavily constrained. Due to complicated modelling showers with zenith angles larger than 60° were omitted. Due to the use of new computation techniques in Auger Project all events will be analysed. In a given energy range, aperture will be two times larger. Modelling of such showers is further complicated by fact that geomagnetic distortions play very important role for horizontal showers and have to be necessarily taken into account.

Most of such horizontal showers will be ordinary hadronic-induced far showers, but small fraction, approximately one thousandth, could be neutrino-induced showers.

Ultra-high energetic neutrinos are very important, because their flux is not influenced by GZK cutoff and they are surely produced in all possible mechanisms of UHECR production. Special importances (due to neutrino types mixing) have τ-neutrinos, because of their large cross-section *[Capelle, K.S. et al., 1998; Bertou, X. et al., 2001]*.

In my further work I want to propose the complex analytical tool for identification of such horizontal events in data from fluorescence telescope. This tool has to be able to discriminate between hadronic showers and neutrino induced showers and allows the comparison with results from surface detector. But this work is just at its starting point.

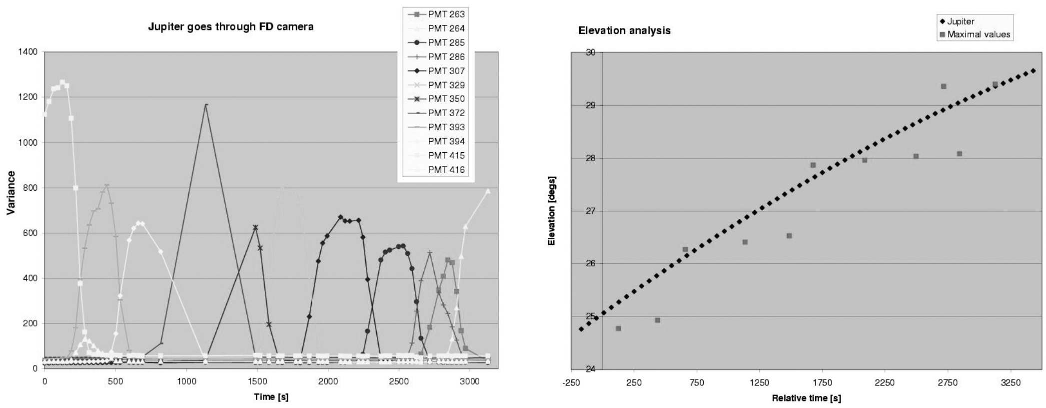

Figure 4. Analysis of star images – preliminary results: Plot of planet Jupiter trailing over individual phototubes *(left)*. *(Right)* Comparison of computed Jupiter azimuth positions (black dots) with measured values (grey dots).

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